Frequency Transfer in Space with GPS Measurements

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BIOGRAPHIES

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ABSTRACT

High precision frequency transfer at the 10^{-16} level onboard the International Space Station (ISS) is required for successful demonstration of the potential ultra-precise reference clocks in space. Three different estimation schemes for frequency transfer in space using GPS measurements are investigated and compared. A covariance/simulation analysis is carried out to assess the potential accuracy for the frequency transfer with simultaneous kinematic determination of the spacecraft orbit. GPS visibility blockage and multipath effects due to the complex spacecraft body, being the major limitation on the frequency transfer accuracy, are assessed with a multipath simulator based on a simplified ISS body. The results of the analysis indicate that 10^{-16}-level frequency transfer accuracy can be attained with a high-quality GPS receiver, proper antenna placement and beam pointing/shaping so as to minimize the observing window blockage and multipath effects, and near-optimal filtering scheme.

INTRODUCTION

The Primary Atomic Reference Clock in Space (PARCS) is a NASA selected flight project for the demonstration of state-of-the-art atomic clock performance in space. The microgravity environment of space allows significant improvements in clock performance over ground-based clocks, thus opening up potential ultra-precise reference clocks in space. The demonstration will be carried out on the International Space Station (ISS) in 2005. It will carry a laser cooled precision clock driven by a hydrogen maser. For the demonstration to be successful, the orbit position is required to be determined to better than 10 cm, the velocity to better than 0.12 mm/sec and the frequency transfer to better than 5×10^{-17} after 12 days. These requirements will be furnished by onboard GPS measurements augmented with the GPS measurements from an existing global network of ground stations.

Precise frequency transfer using GPS has been demonstrated between terrestrial sites hundreds to thousands of kilometers apart. Frequency transfer to 10^{-15} accuracy has been reported [1]. The accuracy has now been even approaching the 10^{-16} level [2]. While the same basic technology can be applied to space environment, limitations exist which will have to be assessed and worked around. First, ISS is in a low orbit with complex dynamics. The orbit has to be kinematically determined [3] which will weaken the orbit solution and the clock transfer capability. Secondly, due to the large and complex ISS spacecraft structure, blockage of GPS visibility will be severe and the signals will experience significant multipath effects.

This paper provides a covariance/simulation analysis assessing the potential accuracy with which ISS orbit determination and frequency transfer can be carried out. A ray tracing technique with a simplified spacecraft structure is used to model the GPS visibility blockage and multipath effects [4,5]. Simulated GPS pseudorange and carrier phase data were generated with the partially blocked GPS viewing geometry. The GPS orbits and clocks were

refined by simultaneous measurements from a global network of ground tracking sties. The results indicate that the requirements can be met with state-of-the-art GPS receiver design, proper antenna placement and beam pointing/shaping, and near-optimal filtering process.

FREQUENCY TRANSFER STRATEGY

ISS will carry a multi-channel dual-frequency GPS receiver capable of acquiring both pseudorange and carrier phase data types. These data contain information of the radiometric distance and clock offset between ISS and GPS. Precise GPS clocks and orbits have been routinely determined with measurements from a dense observing network of global sites. Hence, the ISS clock can be determined with high precision if accompanied by precise determination of ISS orbit. Therefore, both ISS clock parameters and orbit will be estimated simultaneously with the GPS data. Precise orbit position and velocity are also a requirement for successful demonstration of PARCS experiment.

The residual errors in GPS orbits and clocks will limit the accuracy of ISS clock and orbit determination. These effects can be minimized by including the GPS data from the whole ground network into the ISS orbit and clock determination process, with GPS orbits and clock parameters being adjusted simultaneously. The locations of a subset of the ground sites will served as reference and left unadjusted; all others are to be adjusted with the same data set. To simplify the analysis, ground data are not included; but the effects of residual errors from GPS orbits and clocks will be assessed.

Since ISS is a large, complex structure accommodating working space scientists in a low Earth orbit, the effects of orbit dynamics are far from being benign. For the orbit to be accurate to the level enabling the precise frequency transfer, it will have to be kinematically determined [3]. In other words, the orbit position at each epoch will be solely determined with onboard GPS data and no dynamics model will be relied upon to relate the position at different epochs.

Long term frequency transfer can be derived from three different estimation schemes, as described in the following.

Scheme 1

Using a GPS data set spanning over a long period of time, estimate a constant clock rate and an additional tightly constrained process-noise clock offset. The solution for the estimated constant clock rate is the quantity of interest, i.e., the frequency. The adjustment of the process-noise clock offset is needed to account for any deviation from a true linear trend of clock drift.

Scheme 2

Pick two GPS data sets at the two ends of the long averaging time, each spanning over a short period of time. With each of these data sets, a single loosely constrained process-noise clock offset is estimated without a constant clock rate. The desired frequency solution can be derived by differencing the clock offset solutions at the two ends of the averaging time.

Scheme 3

Divide the data over the whole averaging time into contiguous data sets, each spanning over a short period of time. With each of these data sets, a single loosely constrained process-noise clock offset is estimated without a constant clock rate. The desired frequency solution can be derived by a linear fit to all these clock offset solutions.

The constraints on clock parameters for the above three schemes are summarized in Table 1. In the following covariance analysis, all three estimation schemes will be investigated and their relative accuracy in ISS frequency determination compared.

Table 1. Constraints on Clock Parameters
(τ = averaging time)

Scheme	Clock offset	Frequency
1	1 cm/sec	$5 \times 10^{-13}/\tau^{1/2}$
2	—	$1 \times 10^{-8}/\tau^{1/2}$
3	—	$1 \times 10^{-8}/\tau^{1/2}$

COVARIANCE ANALYSIS

ISS is assumed to have a low circular orbit at a nominal altitude of 407 km. The orbit elements at an arbitrarily chosen epoch of 1998:09:22 00:00:00 UTC are assumed as shown in Table 1. The orbit was integrated forward over 7 days and served as the nominal ISS orbit.

Table 2. Epoch Satellite Orbit Elements

Semi-major axis	6785 km
Eccentricity	0.02
Inclination	51.6°
Argument of Periapsis	90°
Right ascension	330°
Mean anomaly	0

Assessment of GPS Orbit and Clock Errors

To assess the significance of GPS orbit and clock errors, ionosphere-free L1-L2 GPS pseudorange and carrier phase data were simulated between ISS and all visible GPS satellites above ISS local horizon at 5-minute intervals

over 1 day. The precise GPS orbits and clocks determined by GPS data from the JPL operated Flinn global network [6] on 1998:09:22 were used as the truth GPS orbits and clocks. The JPL's quick-look GPS orbits and clocks were used as the nominal GPS orbits and clocks from which the computed observables and partial derivatives are calculated. The difference in these two sets of orbits (and clocks) has an RMS value of about 20 cm.

The pseudorange data were weighted at 0.5 m. Although carrier phase data can be as good as a few mm, they were weighted only at a 5-cm level to closely reflect the effects of GPS orbit and clock errors on the data. In this analysis, the only parameters to be estimated are ISS states and clock parameters. The clock behavior was estimated at each of the 5-minute data sampling points, with two different modeling constraints as described in Schemes 1 and 2 of Table 1.

Fig. 1 compares the RMS value of ISS clock offset determination errors due to data noise and GPS orbits. Note that with Scheme 1, the errors do not account for the clock rate which was also estimated. With either estimation scheme, the GPS orbits and clocks have a lesser effects on ISS clock determination. The actual GPS orbits and clock errors can be a factor of 4–5 better when determined with a dense ground network [6]. In the following analysis, the effects of GPS orbits and clocks will be ignored and hence no ground data included.
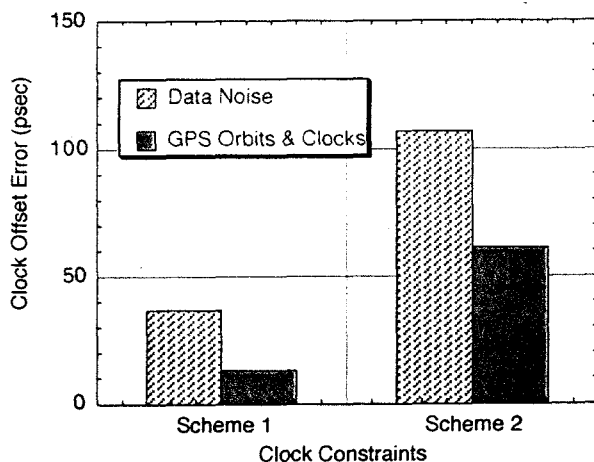

Fig. 1. Comparison of data noise and GPS orbit/clock error on ISS clock estimation

Frequency Transfer Accuracy

For this analysis, ionosphere-free L1-L2 GPS pseudorange and carrier phase data were simulated between ISS and all visible GPS satellites above ISS local horizon at 5-minute intervals over a 7-day period.

With Scheme 1, different data spans from 0.5 hour to 7 days were used for the determination of ISS orbit, a constant clock rate and a tightly constrained process-noise clock offset. The results, as shown in Fig. 2, indicate that the frequency determination accuracy has a trend $\sigma_f \sim T^{-0.7}$ as a function of data span T. A simple extrapolation dictates that a data set spanning over a 60-day period would be required for the frequency determination accuracy to be at the 10^{-16} level.
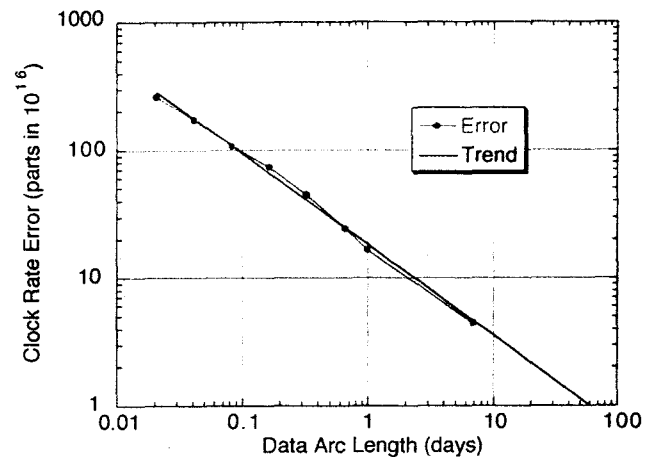

Fig. 2. Frequency transfer accuracy with Scheme 1

With Scheme 2 and 3, different data spans from 0.5 hour to 1 day were used for the determination of ISS orbit and a single loosely constrained process-noise clock offset. The results, as shown in Fig. 3, indicate that the clock error decreases to ~100 psec with a data span of ~4 hours. Increasing the data span beyond ~4 hours does not show any significant improvement on the clock determination accuracy. Hence, the optimum data span is at ~4 hours.
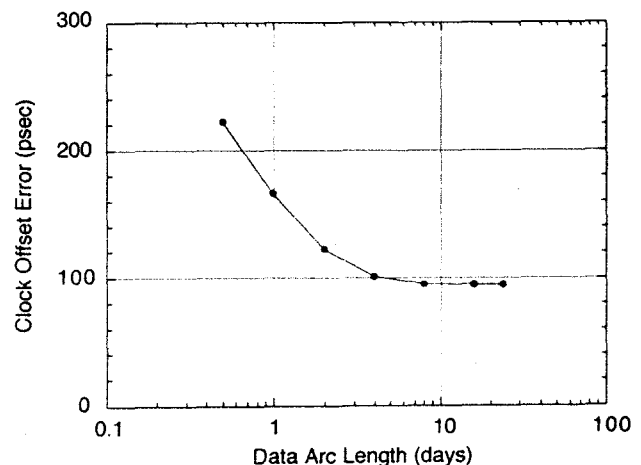

Fig. 3. Clock offset determination accuracy with Scheme 2 and Scheme 3

The frequency transfer accuracy with Scheme 2 and 3 are summarized in Fig. 4 as a function of averaging ime. With Scheme 2, a 16-day separation between the two data spans will be required for a 10^{-16} accuracy. With Scheme 3, a 10-day data span will yield a frequency transfer accuracy of 0.5×10^{-16}.
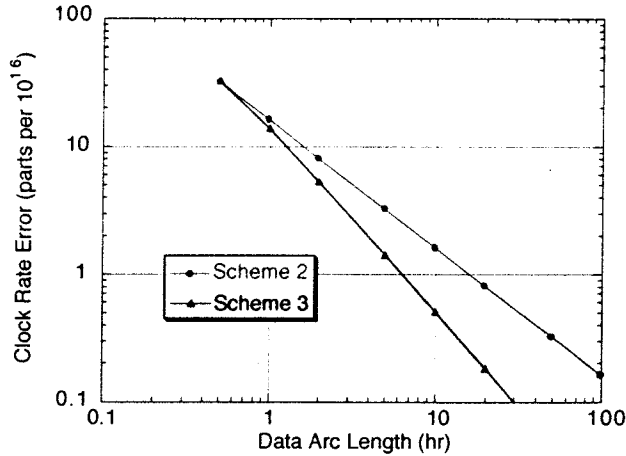

Fig. 4. Frequency transfer accuracy with Scheme 2 and Scheme 3

From the above analysis, it appears that Scheme 3 is superior to the other two estimation schemes and is potentially capable of 10^{-16} frequency transfer accuracy.

GPS VISIBILITY BLOCKAGE AND MULTIPATH EFFECTS

In the above analysis, two assumptions have been made for simplicity: (1) the GPS antenna onboard ISS has a clear view window above its local horizon and (2) no multipath effects due to signal reflections from the surrounding objects are considered. In fact, ISS is a complex structure with several body modules and large solar panels. The available onboard GPS antenna location is limited and is far from being optimal. For a realistic assessment of the frequency transfer accuracy, these two aspects have to be investigated.

GPS Visibility Blockage

To simulate the GPS satellite visibility of the on-board antenna we have considered the antenna surrounding object as well as the four large solar panels of ISS. Two different cases were considered depending the orientation of the solar panels: 1) Best visibility case and 2) Worst visibility case. The best case is when the solar panels are parallel to the flight direction of the ISS; the worst case is when the solar panels are about 45 degrees above to the flight path.

Figs. 5 and 6 show the best and the worst visibility cases, respectively. The triangular shapes denote the limiting elevation angle at a given azimuth angle. Any GPS

satellite with local elevation angle lower than the limiting angle at the corresponding azimuth angle is not visible to the receiver. In the figures the positive x-axis denotes the flight direction and the antenna has good visibility in that direction. The blockage in the negative x-axis direction is due to the fixed structures near the antenna. The blockage in y-axis direction is due to the solar panels.
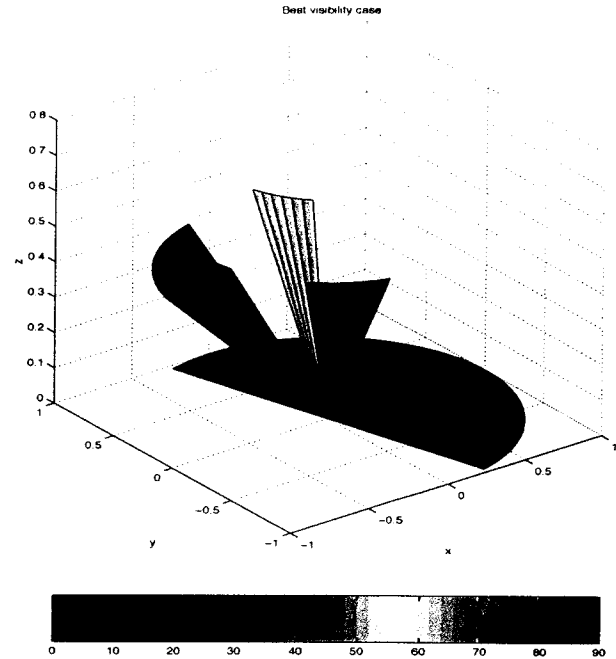
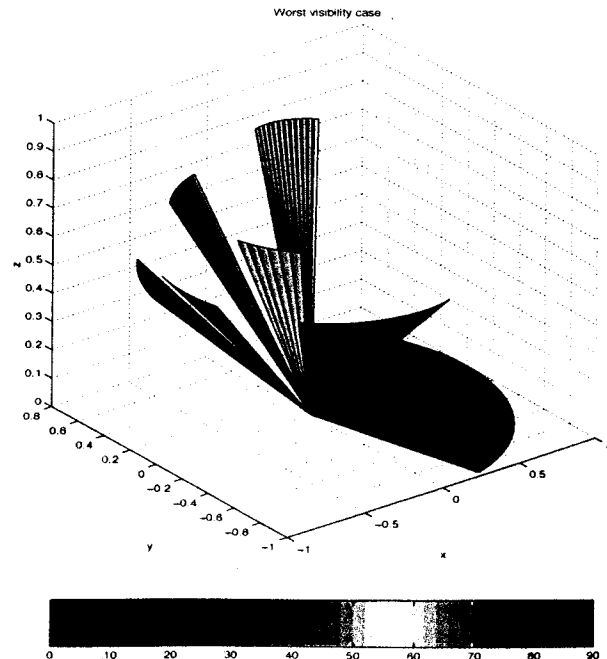

Fig. 5. Best case GPS visibility blockage

Fig. 6. Worst case GPS visibility blockage

Fig. 7 shows the number of visible GPS satellites above the ISS local horizon. Note that the worst-case blockage reduces the number of visible GPS satellites by more than 50%.
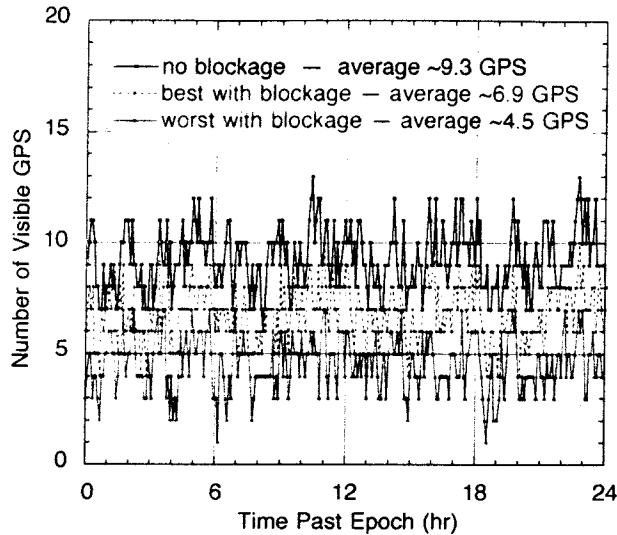

Fig. 7. GPS visibility above ISS local horizon

Simulation of Multipath Effects

Multipath is the phenomenon where a signal arrives at an antenna via several paths due to signal reflection and diffraction. The signal waveform's amplitude and phase can be significantly distorted by these secondary paths and thus can result in significant ranging errors. The multipath is a highly localized phenomenon and can be one of the major error contributors to GPS positioning application. In order to examine the multipath effects on the GPS signal and their implications on positioning solution, the multipath simulator, MUSTARD (Multipath Simulator Taking into Account Reflection and Diffraction), has been developed at the Jet Propulsion Laboratory [4].

In essence, the simulator traces the signal as it is transmitted by the GPS satellite to a user's receiver. It accounts for all possible different paths possible due to specular reflection or diffraction from the surrounding surfaces. In order to account for reflection and diffraction, the Geometrical Theory of Diffraction (GTD) is used [7]. This sets a lower limit of few wave lengths on the size of the reflection objects. The multipath signals are then added to the direct signal after accounting for the gain of the receiving antenna and, then, range and phase errors measured by the receiver are estimated. This is done for both L1 and L2 frequencies.

With this information, we may attempt to modify the structural configuration if possible or recommend the best antenna type, location, and orientation within the given configuration. This multipath simulator gives a realistic estimate of the error introduced by multipath, and helps finding means of minimizing the effect of multipath. By analyzing the real GPS data at the OVRO site, Hajj [5] showed that MUSTARD could simulate very reasonable multipath error.

In simulating the multipath signal, we can define the configuration and geometry of the main objects that are expected to cause multipath. This can be defined in terms of surfaces of objects that are potential sources of multipath. The simulator uses simplified model of the real multipath environment where the characteristic geometry of the signal reflecting structure is represented. The multipath environment is generally modeled as a finite number of surfaces whose dimensions, relative locations, as well as their reflectivity and refractivity properties are specified. In fact, some simplifying assumptions can be made to approximate the complicated structure of the multipath environment and, usually, two criteria are applied in modeling the structure: First, only surfaces that are potential contributors to multipath are modeled. Second, since only surface with dimensions equal or larger than one wavelength can be modeled accurately with the geometric theory of diffraction, the diffractions from small objects surrounding the GPS antenna are accounted for by considering a large, perfectly conducting flat surface covering these objects. We believe that this approximation would set an upper limit on the multipath error since there would be a single strong reflection from this surface compared to multiple weaker reflections from several objects that would tend to cancel.

Both specular reflection and diffraction from edges are considered. Since the transmitted GPS signal is nearly purely right-hand circularly polarized (RCP), the incident signal will always be assumed purely RCP. Assuming the surface to be a perfect conductor, then the specularly reflected signals are completely left-hand circularly polarized (LCP) with the same power as the direct signal. In practice, however, the reflected signal is attenuated and composed of both RCP and LCP components. To compute the range errors due to multipath from a given signal reflection, we can look at the correlation function of the direct and the reflected signal, and determine how far the correlation peak shifts to obtain the range error. The total range error is the sum of both the reflected and the diffracted multipaths which are assumed to be uncorrelated.

For the PARCS experiment, the GPS antenna will be located at Japanese Experiment Module (JEM) where the multipath interference is inevitable. For the environmental modeling of JEM, simplified models of three major multipath sources were considered as shown in Fig. 8. They are stationary objects close to GPS antenna and consists of Pressurized Module (PM), Exposed Facility (EF), and Experiment Logistics Module (ELM). The dimensions and the relative locations of the modules can be found at

http://jem.tksc.nasda.go.jp/iss/doc09_e.html.

Pressureized Module

GPS antenna

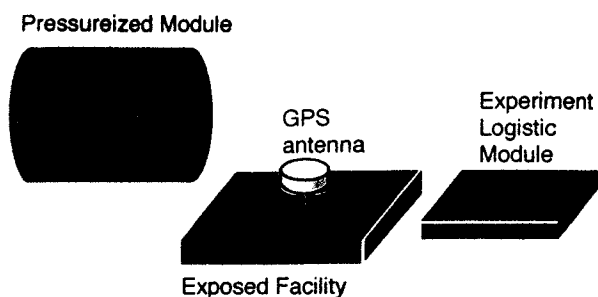Experiment Logistic Module

Exposed Facility

Fig. 8. Simplified ISS modules (not to scale)
for multipath simulation

The on-board GPS receiver is assumed to track all visible GPS satellites. The antenna is assumed to be placed at the center of EF with one meter height. Fig. 9 shows the multipath induced range error for the ionospheric free pseudorange and carrier phase observables.
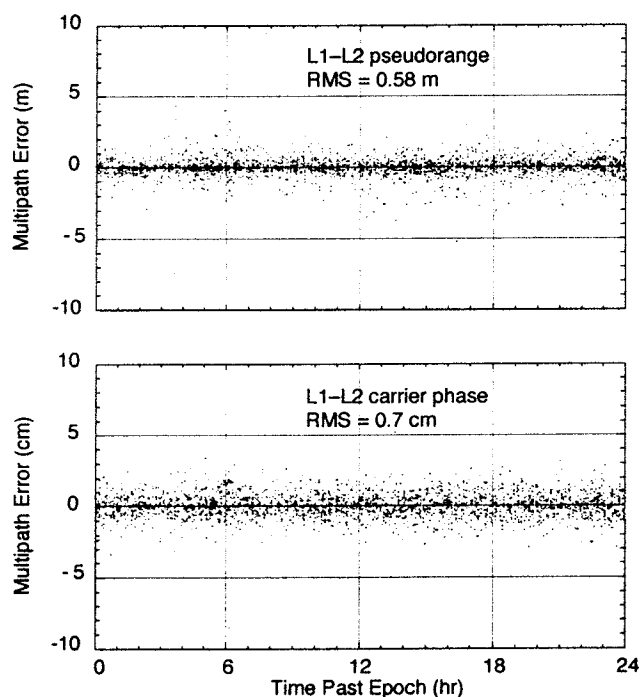
L1–L2 pseudorange
RMS = 0.58 m

Multipath Error (m)

L1–L2 carrier phase
RMS = 0.7 cm

Multipath Error (cm)

Time Past Epoch (hr)

Fig. 9. Simulated multipath errors on GPS data

Effects on Frequency Transfer and Orbit Determination

The covariance analysis with Scheme 2 and 3 are repeated with the effects of GPS visibility blockage and multipath errors included. The results shows that the clock offset estimation accuracy degrades by a factor of 2.5 and 40, respectively, for the best and worst visibility blockage cases.

A close look into Figs. 5 and 6 show that the visibility blockage is least severe in the forward (+x) direction. Tilting the GPS antenna forward should result in a better observing geometry. When the GPS antenna is tilted forward by 15°, the clock offset estimation accuracy with the worst-case visibility blockage degrades to only a factor of 6 higher than the case without blockage and multipath errors. The ISS orbit solution has an RMS position error of 28 cm and an RMS velocity error of 0.76 mm/sec, as shown in Fig 10. These values are higher than the 10 cm and 0.12 mm/sec requirements. However, this represents the worst geometry which will occur only infrequently. A GPS data set spanning a total of 12–15 days is believed to be sufficient to yield a frequency transfer accuracy of 10^{-16}. Better antenna pointing and/or beam shaping will help improve the estimation capability.
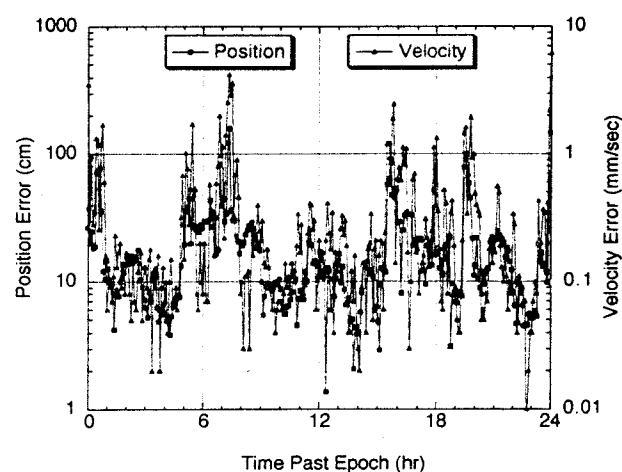
Position   Velocity

Position Error (cm)

Velocity Error (mm/sec)

Time Past Epoch (hr)

Fig. 10. ISS orbit determination accuracy with 15°-tilt
GPS antenna under worst visibility case

CONCLUSIONS

High precision frequency transfer on the International Space Station with GPS measurements is a challenging task. The large and complex spacecraft structure, together with the undesirable location of the GPS antenna, presents a problem of serious GPS visibility blockage.

A comprehensive covariance/simulation analysis has been carried out to assess the potential accuracy for frequency transfer onboard ISS. The results of this analysis indicate that while it is not impossible to attain a frequency transfer at the 10^{-16} level, it requires a state-of-the-art GPS receiver, proper pointing of the GPS antenna, careful treatment of multipath effects, and a near-optimal filtering scheme. The overall performance can also be vastly improved with the use of precise onboard accelerometers, so that dynamic orbit determination can be used in place of the kinematic approach assumed in the current analysis.

ACKNOWLEDGMENT

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